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Optical Fiber to Waveguide Coupling Technique

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SUMMARY

This report investigated and demonstrated the feasibility of a technique for permanently coupling optical fibers edge-on to thin-film waveguides.

The technique offers fine micropositioner adjustment via a needle vacuum chuck for maximum optical coupling, offers robust mechanical support to the fibers from etched Si V-grooves, separates the support and fine adjustment cementing steps to minimize curing and thermal stresses, relaxes the requirements on fiber circularity and concentricity, is compatible with waveguide devices, and is suitable for close-spaced arrays of fibers.

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INTRODUCTION

Emerging optical waveguide devices appear attractive as terminal elements in optical fiber transmission, sensing, and signal processing applications. Such use naturally depends upon the permanent coupling of single-mode optical fibers to channel thin-film waveguides, which is the subject of this paper. The purpose of this effort was to investigate a technique for optical fiber to channel waveguide coupling, emphasizing suitability to different waveguide materials, stability, and producibility while being compatible with methods to obtain maximum coupling efficiency and with waveguide device requirements such as electrical access.

Fiber coupling to thin-film waveguides can be done via evanescent wave coupling between the two waveguides or by end-on launching. End-on coupling was chosen for its simplicity and its suitability to different waveguide materials. The approach conceived and developed here involves cementing the fibers in etched Si grooves with ultraviolet (UV)-curing adhesive for coarse positioning and mechanical support. Subsequent fine positioning of a fiber is done with a needle vacuum chuck on a micromanipulator followed by an final cementing step. Many fibers can be coupled to a waveguide chip facet with this technique.

We investigated this technique experimentally, fabricating and testing three fiber–film assemblies. Single-mode optical fibers and thin-film channel waveguides in the 830-nm wavelength region were used. We chose channel waveguides fabricated in $LiNbO_3$ by Ti indiffusion ($Ti:LiNbO_3$), since they are widely used for active and passive thin-film devices. We conclude that the coupling assembly process is feasible and offers attractive features, including

- fine optical coupling adjustment separate from fiber support,
- optical coupling maximized from in situ transmission,
- minimized adhesive and thermal stress,
- suitability for different waveguide materials, and
- suitability for close-spaced fiber arrays.

Development of this technique would include further investigation of these features and how they affect attendant packaging and performance issues such as reliability, environmental effects, producibility, compatibility, and optical coupling efficiency.

BACKGROUND

In recent years, more research has been devoted to this subject (references 1 and 2), concentrating on coupling efficiency in the end-on configuration, which is practical and not material specific. This efficiency is vital and clearly a challenge since the optical waveguides are microns in size, mode patterns from two different types of waveguides must be matched, and film and fiber edge conditions must be controlled. The best figures reported for Ti:$LiNbO_3$ waveguides are 95% (-0.2 dB) coupling efficiency at λ = 633 nm (reference 3) and a fiber waveguide fiber insertion loss of 1 dB for a 1-cm-long waveguide at λ = 1320 nm (reference 2). Micromanipulators were used to position the fibers in these experiments.

These figures exceed theoretical estimates for this coupling (reference 4), that involve calculation of the overlap integral of the fiber and channel waveguide modes. The transverse fields of these optical modes are modeled as circular and rectangular Gaussian functions respectively. Optimum conditions for coupling were calculated as well as the adverse effects of waveguide tilt, offset, and end separation. For example, to keep each of these loss contributions below 10% (-0.5 dB) for typical Ti:$LiNbO_3$ waveguides and fibers, the tilt should be less than about 1 degree, the offset less than about 0.8 μm, and the end separation less than about 20 μm (references 1 and 5).

Although low-loss, adjustable connectors have been reported for fiber-film coupling, techniques for permanent joining of many fibers to a thin-film waveguide chip are needed ultimately. The first adjustable connector applied double eccentric cylindrical supports permitting the alignment of two single-mode waveguide components (reference 6). A second approach uses etched Si V-grooves for fiber positioning (reference 7), a flip-chip orientation for the thin film channel waveguides, and tapered fibers transverse to the coupling fibers for fine height adjustment (reference 8). These techniques appear limited to one or two fibers per chip facet.

Several approaches for attaching fibers permanently to $LiNbO_3$ channel waveguides have been implemented in varying degrees. One coupler (reference 9) holds the fiber in place with a jig attached to the chip carrier. Fine adjustment is accomplished by set screws, and a final step of plastic molding fixes the fiber in place. This is not suitable for more than one or two fibers per chip edge owing to the size of the positioning fixture.

Other techniques use Si V-grooves to support fibers in positions determined by photolithographic masking and preferential chemical etching. The grooves can be defined to the same accuracy as the channel waveguide lithography, and the etching has excellent control and reproducibility. In this scheme, the accuracy of a fiber core position naturally depends upon the uniformity of the fiber outer diameter (OD) and its concentricity with the core. Various methods are used for aligning the Si carrier chip with the waveguide chip and, subsequently, cementing them.

One coupler (reference 10) uses etched V-grooves in Si for both fiber holding and as alignment markers to bring the flip-chip $LiNbO_3$ waveguides into proper registration before cementing. Fibers were then placed in the grooves; permanent attachment was not reported. A second coupler (reference 11) approach epoxies the fibers in the V-grooves and polishes the Si and fiber end surfaces flat together. Then the Si chip is epoxied to a holder, which offers micrometer adjustment in the transverse directions after the epoxy has cured. An initial version had an external micropositioner, which adjusted the Si chip into place and was removed after the epoxy step. However, this arrangement suffered misalignment from stress placed on the Si chip by the curing epoxy.

A third example is a waveguide switch network coupled to four output fibers (reference 12). The fibers are sandwiched between two Si chips etched with V-grooves, and the chips are positioned

and epoxied to a mount carrying the switch chip. Mention was made of difficulty in epoxying the fibers and Si chips for fine positioning, but details were not given.

To summarize, these methods for permanently attaching multiple fibers depend upon aligning them relative to each other by their ODs using the very accurate Si V-grooves. Thus, the core locations depend upon the fiber qualities of uniformity and concentricity. The Si chip is then positioned to align the V-grooves or the fibers in them with the channel waveguides and adhesive is applied to fix positions. The chip positioning can be done well within the required accuracy but stress from the curing epoxy causes misalignment. One approach retains fine adjustment, which is a disadvantage but may be tolerated in certain applications.

COUPLING TECHNIQUE

The approach taken in this work is designed to retain the considerable advantage of Si V-grooves in supporting fiber arrays; retain fine micromanipulator final adjustment to accommodate imperfections in fibers, V-grooves, and channel waveguide positions; and minimize stress from adhesive curing and thermal changes. Figure 1 illustrates the concept. The fibers are completely supported by V-grooves in the Si chip, which is placed up to about 10 mm from the waveguide chip facet. The concept is made attractive by the introduction of the needle vacuum chuck, which grasps each fiber providing micromanipulator fine control to its alignment while it is cemented to the waveguide chip. Upon maximization of light transmitted through the fiber waveguide assembly, UV light is applied to cure the adhesive and the vacuum chuck is subsequently released. The V-groove alignment may be relatively coarse, <10 μm. The height is determined by the V-groove depth, the thickness of both chips, and the cement thickness between the chips and chip carrier. The transverse and angular alignment of the V-grooves and waveguides can be done by bringing them into registration with a microscope filar or by reference to chip edges, other grooves, or lithographic markers.

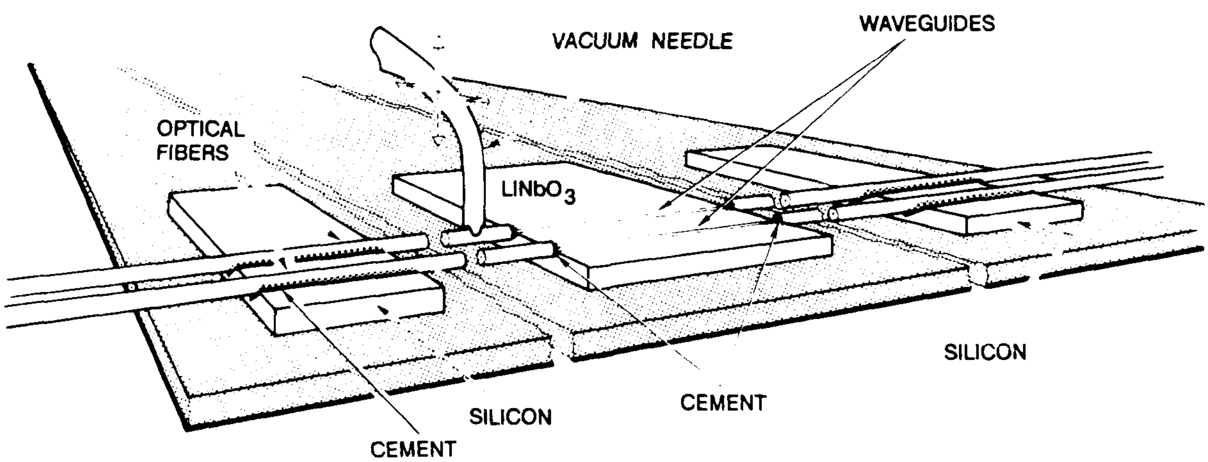

Figure 1. Fiber waveguide coupling schematic.

There are two possible sequences for bonding the fibers, fixing the fiber end first or last. First a fiber is placed in the V-groove, a small amount of adhesive is applied to just cover the fiber end face, and the fiber is moved by the vacuum chuck into its final position where the adhesive fills the fiber-chip gap, of about 10 μm. Adhesive is added to the V-groove surrounding the fiber, and UV light is applied curing the adhesive in the gap and then in the grooves. In the second case, the fiber is

positioned in the V-groove and cemented. Then adhesive is applied to the fiber-chip gap and it is cured after fine alignment by the vacuum chuck. This has added flexibility in that fiber or fibers can be cemented into a Si carrier and remain for an arbitrary curing period after which the final fiber end positioning and cementing can be performed. The application of cement to the fiber-film gap requires an extra step in this version. The cement can be applied to the gap itself, or the fiber can be raised above the waveguide chip by the vacuum chuck, exposing the fiber face for the application of cement. In either case, the technique for applying only the minimum amount of cement requires attention.

Therefore, by separating the V-groove fiber support from the fine-positioned fiber end by a distance of 50 to 100 fiber diameters, stress of final fiber alignment and long-term cement curing at the V-grooves upon the fiber-waveguide coupling are minimized. Furthermore, applying the adhesive only to fill the fiber-chip gap minimizes any curing stress at that point, furnishes sufficient strength to maintain the fiber in its fine-positioned place, and provides some index matching for the optical coupling. By using the small needle vacuum chuck, we are able to manipulate a fiber in a closely spaced array, cement it, and withdraw with no disturbance.

EXPERIMENTS

The experiments are described beginning with the components and their assembly and followed by results and recommendations. The main elements are the needle vacuum chuck, the etched Si V-grooves, UV-curing optical cement, $Ti:LiNbO_3$ channel waveguides, and the optical fibers. The needle vacuum chuck was adapted from one used for handling semiconductor chips. It had an OD of 375 μm and inside diameter (ID) of 225 μm, shown in figure 2, and a groove was filed across a diameter to conform to the cylindrical shape of the fiber. A standard vacuum pump was attached via flexible plastic tubing. The force exerted on the fiber was sufficient to lift it, although this is more than is required for its positioning. Fibers can be spaced together down to the needle outer radius plus the fine movement necessary for final positioning. For the needle, fiber, and typical adjustments used, this would amount to -325 μm fiber center-to-center spacing. Evidently there is room to reduce this figure through use of smaller needles and better V-groove-to-waveguide alignment.

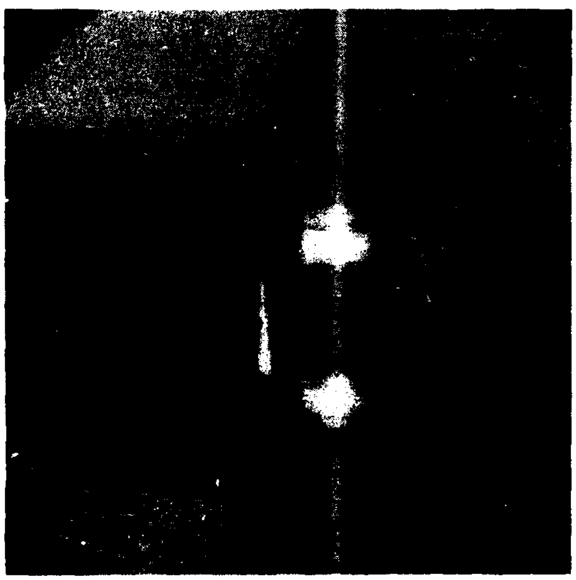

Figure 2. The needle vacuum chuck with a fiber.

The Si V-grooves were etched in the usual way through a 1-μm-thick SiO_2 pattern fabricated by photolithographic techniques. The etchant was KOH, and the chip had 100 orientation. Figure 3 shows the typical well-defined V-groove with its 70.5-degree vertex angle. The optical cement used was Norland Optical Adhesive 61, a one-part liquid photopolymer that cures when exposed to UV light. Characteristics reported by the manufacturer (reference 13) include good adhesion, low shrinkage, flexibility, and n~1.5. It is usable in interferometric applications (reference 14). Using a UV source of 1 mW/cm_2, we precured for about 2 minutes and cured for about 15 minutes.

Figure 3. V-groove etched in Si.

A Corning optical fiber was used with a 780-nm cutoff, 8-μm core, and 125-μm OD. Attenuation was quoted at 8.7 dB/km, and the plastic coating could be removed mechanically or with acetone. Fiber ends were cleaved by the well-known manual scribe and break method. The fiber end surfaces were tested by an interferometer, which measured their flatness and perpendicularity to the fiber axis (reference 15).

Channel waveguides for the investigation were fabricated by Ti indiffusion in Z-cut $LiNbO_3$ 2.0 cm long. Widths ranged from 4 to 8 μm and their attenuation was estimated to be a few dB/cm, which is high compared with recent results (references 11 and 12). Conventional polishing techniques were applied to their entrance and exit facets to give nearly featureless edges under 600 X optical magnification (references 16 and 17). These waveguides supported a few modes at 633 nm and were single mode at 830 nm.

The $LiNbO_3$ chip, the Si V-groove chip, and the optical fibers were assembled, supported by a microscope slide chosen for experimental convenience. The $LiNbO_3$ chip was cemented with the channel waveguides positioned parallel to a reference edge on the microscope slide. A simple jig positioned another reference edge parallel to the $LiNbO_3$ entrance facet so that the Si chip could slide along it at the desired distance. Since the Si can be etched and cleaved along photolithographically defined lines, this allows us to maintain the grooves and channel waveguides parallel while sliding them into transverse alignment. The Ti:$LiNbO_3$ waveguides are readily observable through a vertical illumination microscope due to the slight bulge created by the Ti indiffusion. In this alignment step, low magnification (10 X) was used to view a spot 2 cm in diameter, which included the V-grooves, the gap, and the waveguides. With a filar eyepiece, one could align the waveguides and the V-grooves to within a 10-μm offset. The Si chip was then cemented in place. Angular alignment is controlled by the assembly fixtures and is easily maintained to within a 1-degree deviation.

Accurate positioning of the fiber in the V-groove requires that it be stripped of its plastic buffer coating. The exposed fiber is weakened, and further support is needed where it emerges from the assembly. We provided a second, larger, in-line, V-groove section etched to hold, cemented, a 5- to 10 mm-long coated length of the fiber. This gave a robust mechanical support that eliminated fiber breakage after attachment and allowed handling of the completed assembly throughout the alignment procedures.

A drop of cement is applied just covering the fiber end, and the fiber is placed in the V-groove where it is grasped 1 to 2 mm from its end by the vacuum chuck. The fiber slides forward in the V-groove until the cement contacts the waveguide chip and the fiber end is within -10 μm of the chip. In the preferred sequence, cement is applied to the V-groove and cured. The optical transmission is then maximized by fine manipulation of the vacuum chuck, the end cement is cured, and the chuck is released. These techniques offer repeatability with a minimum of critical adjustments and adaptability to batch fabrication.

Three assemblies were made. Two were aligned with a 633-nm light, although the fiber cut-off wavelength was at 780 nm. One assembly had a single fiber, and the other had four fibers attached as seen in figures 4 and 5. Loss measurements were made on the single-fiber assembly using the cutback method. This technique involves launching light into the fiber and measuring the intensity transmitted through the assembly and emerging from the channel waveguide. Then without disturbing the launch conditions, one cuts the fiber and the intensity emerging from it is measured, yielding the input intensity, which may then be compared to the transmitted intensity. This measurement at 633-nm wavelength yielded $\approx$11 dB loss.

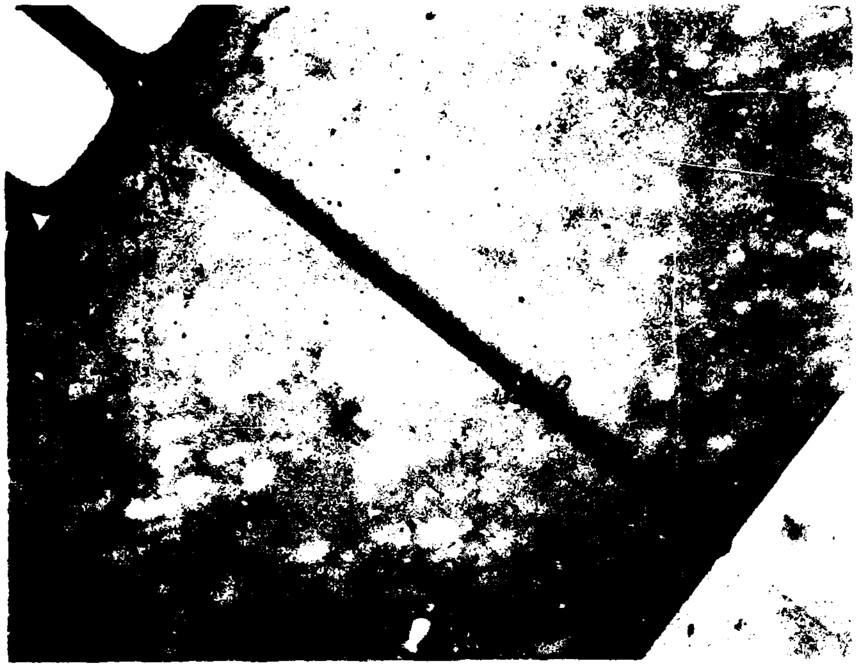

Figure 4a. Single-fiber assembly showing V-groove upper left, fiber and waveguide at lower right.

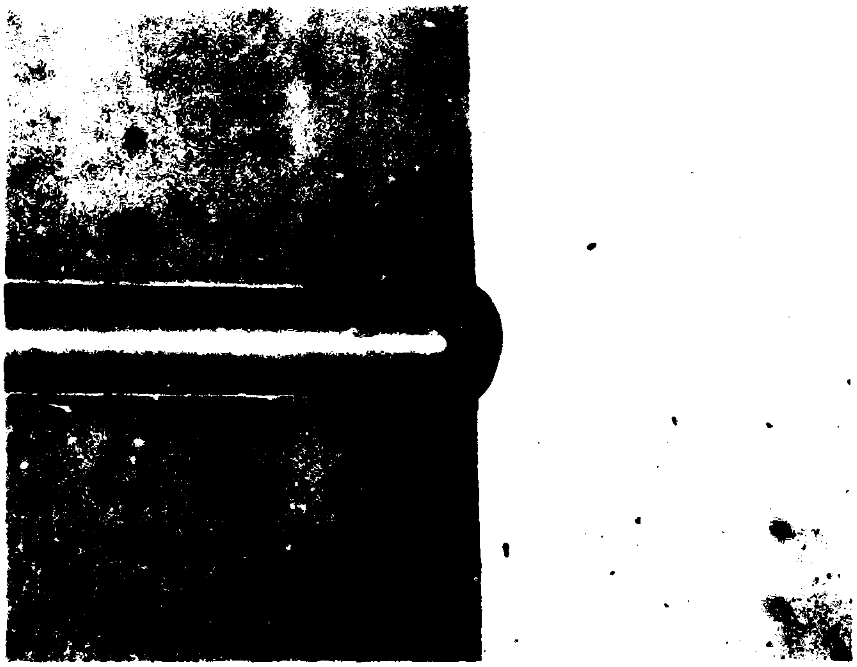

Figure 4b. Single-fiber assembly showing closeup of fiber and waveguide.

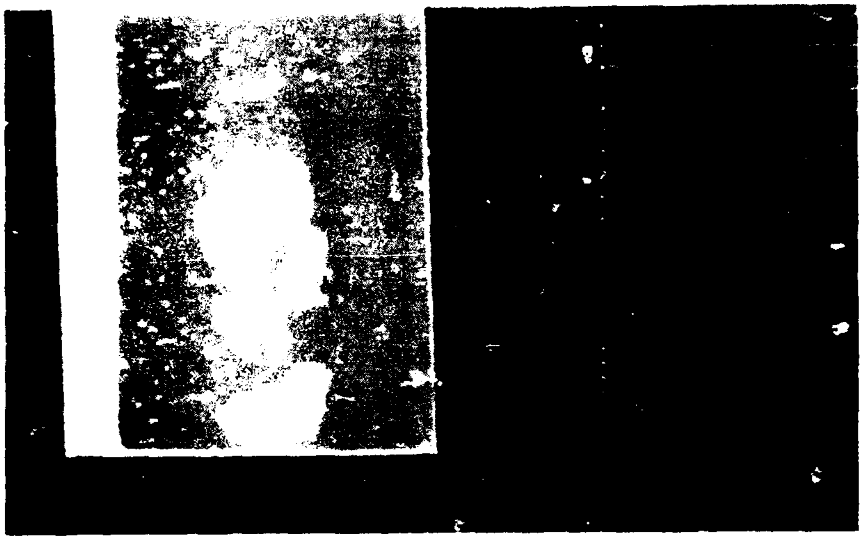

Figure 5. Four-fiber assembly.

The second single-fiber assembly, shown in figure 6, was characterized at 830 nm by the insertion loss as well as the cut-back method. In measuring insertion loss, light is launched into the fiber before assembly, and its output intensity is recorded. After cementing, the emerging light from the channel waveguide is recorded, and the two are compared. Both techniques yielded $\approx$9 dB loss. We attempted to determine the waveguide propagation loss by measuring the scattering loss along the waveguide length with a transverse optical fiber probe. However the waveguide scattering was too small for this technique, and thus we were unable to separate coupling from propagation losses.

We found this method of ass nbly and attachment feasible and recommend further development, which would include effort and investigation into the following areas:

- environmental effects upon the assembly,
- long-term stability,
- mechanization of processing and assembly steps,
- coupling efficiency, and
- fiber arrays.

To summarize, we ha e implemented a new permanent assembly technique for edge-on coupling of single-mode optical fibers to thin-film channel waveguides. It offers robust mechanical support to the fibers from etched Si V-grooves, provides the fine micropositioner adjustment via a needle vacuum chuck for maximum optical coupling, separates the support and fine adjustment cementing steps to minimize curing and thermal stresses, relaxes the requirements on fiber circularity and concentricity, is compatible with waveguide device requirements, and is suitable for close-spaced arrays of fibers. This feasibility demonstration indicates that the approach offers a great deal of promise and should be pursued.

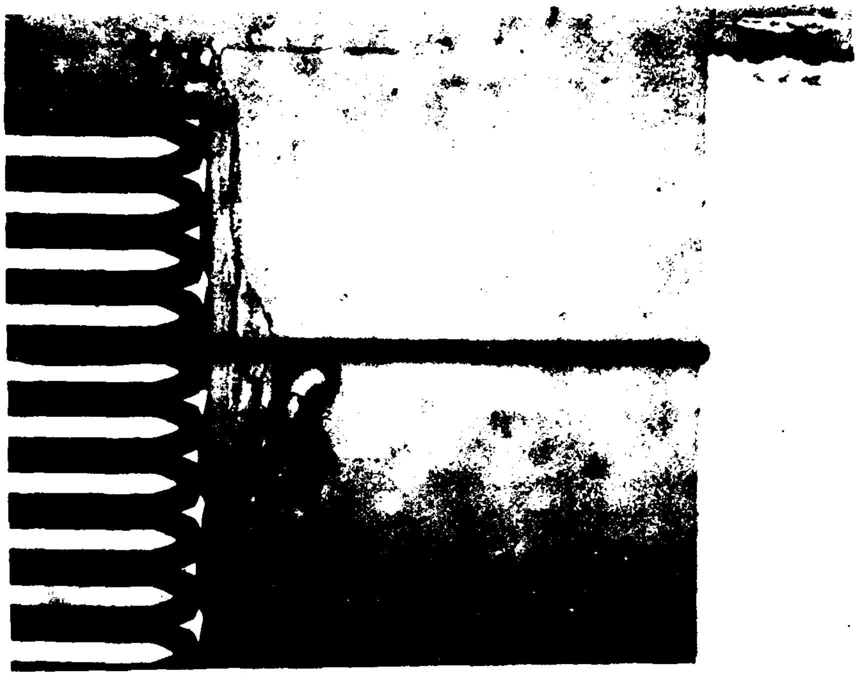

Figure 6. Single-fiber assembly showing V-groove, fiber and waveguide.

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13. ABSTRACT *(Maximum 200 words)*

A technique for permanently coupling optical fibers edge-on to thin-film waveguides was investigated and its feasibility demonstrated. It offers the fine micropositioner adjustment via a needle vacuum chuck for maximum optical coupling, offers robust mechanical support to the fibers from etched Si V-grooves, separates the support and fine adjustment cementing steps to minimize curing and thermal stresses, relaxes the requirements on fiber circularity and concentricity, is compatible with waveguide devices, and is suitable for close-spaced arrays of fibers.

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